

FT4 Data Analysis Summary (SSI-ARC)

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Abstract

Standards for Unmanned Aircraft System (UAS) Detect-and-Avoid (DAA) systems are currently being developed under the auspices of the RTCA Special Committee 228 (SC-228). To support the development of these standards, a series of flight tests has been conducted at NASA's Armstrong Flight Research Center (NASA-AFRC). The fourth in this series of flight test activities (Flight Test 4, or simply FT4) was conducted during the Spring and Summer of 2016. FT4 supported the objectives of numerous organizations working toward UAS DAA Minimum Operational Performance Standards (MOPS) and UAS DAA Radar MOPS. The summary provided herein is limited to the objectives, analysis and conclusions of the NASA Ames Research Center (NASA-ARC) SSI team toward the refinement of UAS DAA MOPS. This document provides a high-level overview of FT4 and the SSI-ARC objectives, a summary of the data analysis methodology and recommendations for UAS DAA MOPS refinements based on the data analysis results. A total of 72 encounters were flown to support SSI-ARC objectives. Test results were generally consistent with acceptable UAS DAA system performance and will be considered in broader SC-228 requirements validation efforts. Observed alert lead times indicated acceptable UAS DAA alerting performance. Effective interoperability between the UAS DAA system and the Traffic Alert and Collision Avoidance System (TCAS) was observed with one notable exception: TCAS Resolutions Advisories (RA) were observed in the absence of any DAA alert on two occasions, indicating the need for alert parameter refinement. Findings further indicated the need for continued work in the areas of DAA Well Clear Recovery logic and alert stability for Mode-C-only intruders. Finally, results demonstrated a high level of compliance with a set of evaluation criteria designed to provide anecdotal evidence of acceptable UAS DAA system performance.






System Under Test: JADEM

FT4 was conducted at NASA-AFRC between April and June of 2016. NASA's Ikhana research aircraft and Ground Control Station (GCS) were equipped with the necessary hardware, displays and software to evaluate three prototype UAS DAA systems: NASA Daedalus, NASA Java Architecture for Detect and Avoid Extensibility and Modeling (JADEM) and General Atomics Aeronautical Systems, Inc. Conflict Prediction and Display System (CPDS). While each system was developed to be as consistent with the developing SC-228 MOPS as practical, there were key differences in their implementation that preclude aggregating FT4 results across the systems under test (SUTs). This document provides the analysis methodology and results for flight testing of the NASA SSI-ARC-developed JADEM system.

Alerting Criteria

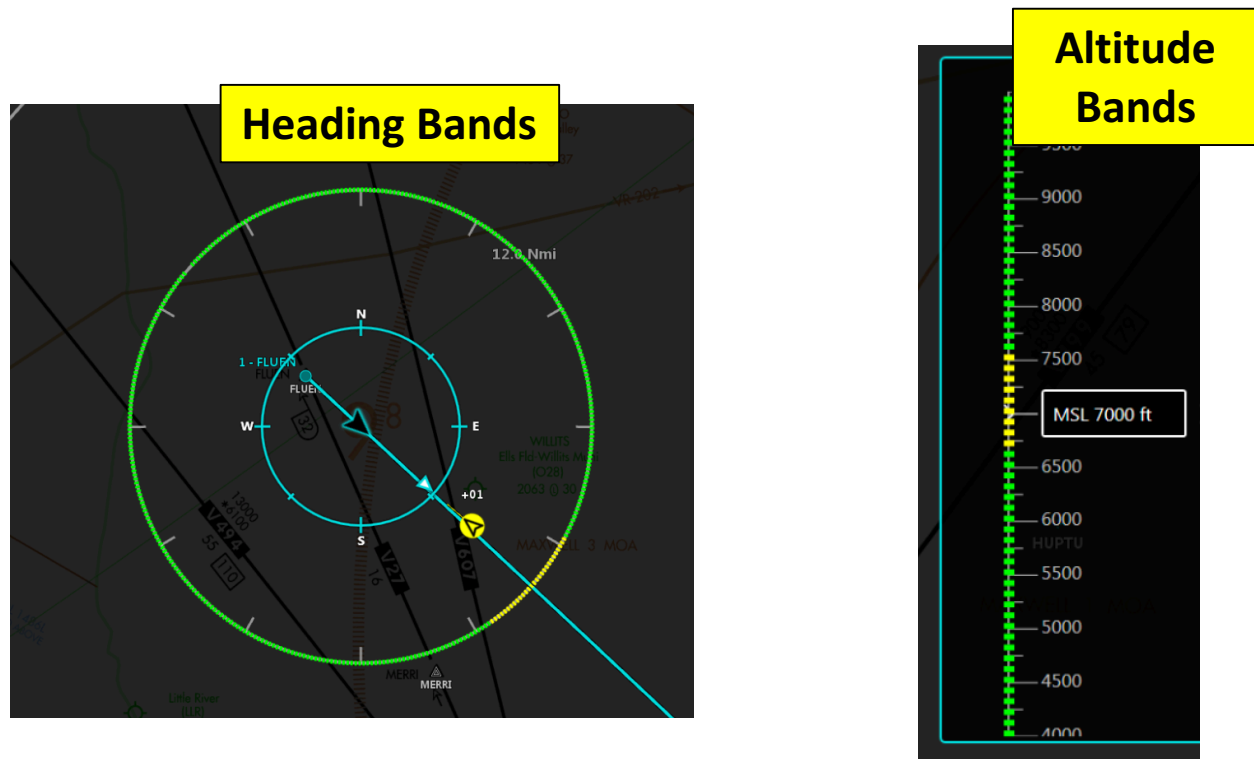
The FT4 JADEM implementation employed the same alerting criteria and display symbology utilized in the NASA Part Task 6 (PT6) study, as shown in Table 1. Alerting hysteresis, as defined in the draft DAA MOPS, was implemented for FT4 (minimum 4-second alert persistence unless superseded by higher priority alert).

Table 1: JADEM FT4 Alerting Criteria

Symbol	Name	Pilot Action	Buffered Well Clear Criteria	Alerting Time Threshold	Aural Alert Verbiage
	TCAS RA	<ul style="list-style-type: none"> • Immediate action required • Comply with RA sense and vertical rate • Notify ATC as soon as practicable after taking action 	(Driven by TCAS-II)	x	"Climb/Descend"
	DAA Warning Alert	<ul style="list-style-type: none"> • Immediate action required • Notify ATC as soon as practicable after taking action 	DMOD = 0.75 nmi HMD = 0.75 nmi ZTHR = 450 ft modTau = 35 sec	25 sec (TCPA approximate: 60 sec)	"Traffic, Maneuver Now"
	Corrective DAA Alert	<ul style="list-style-type: none"> • On current course, corrective action required • Coordinate with ATC to determine an appropriate maneuver 	DMOD = 0.75 nmi HMD = 0.75 nmi ZTHR = 450 ft modTau = 35 sec	55 sec (TCPA approximate: 90 sec)	"Traffic, Avoid"
	Preventive DAA Alert	<ul style="list-style-type: none"> • On current course, corrective action should not be required • Monitor for intruder course changes • Talk with ATC if desired 	DMOD = 1.0 nmi HMD = 1.0 nmi ZTHR = 700 ft modTau = 35 sec	55 sec (TCPA approximate: 90 sec)	"Traffic, Monitor"
	Remaining Traffic	<ul style="list-style-type: none"> • No action expected 	Within surveillance field of regard	x	N/A

Omnibands Guidance

The JADEM system provides guidance to the UAS pilot in the form of heading/altitude bands, the color of which indicates the level of alert that would result if the ownship were to initiate a turn/altitude-change to the heading/altitude depicted. Green banding indicates a turn/altitude change to the depicted heading/altitude is not predicted to result in a Loss of Well Clear (LoWC). Yellow banding indicates a turn/altitude-change is predicted to cause a DAA Corrective Alert (i.e. potential LoWC in the next 25-55s). Lastly, red banding indicates a turn/altitude-change is predicted to cause a DAA Warning Alert (i.e. potential LoWC in the next 25 s or less). Figure 1 depicts sample Omnibands guidance as would be displayed in the UAS GCS; a "Corrective" DAA Alert is displayed for the only displayed intruder. The guidance illustrated in Figure 1 indicates viable maneuvers to remain well clear are available in both the heading (~15 degrees left or right) and altitude (+600 ft or -400 ft) bands.



Omnibands guidance for multiple intruders is produced by forming the union of individual omnibands guidance for each intruder within the field of regard, with higher priority alerts overriding lower priorities when alerts differ between intruders for a given heading/altitude level. Additionally, the following assumptions and parameters were used in the JADEM guidance and alerting logic for FT4:

1. Ownship assumed to execute turns at a constant rate of 3 deg/s
2. Ownship assumed to climb or descend at constant rate of 1000 ft/min
3. Omnibands heading guidance limited within +/- 100 degrees of current ownship heading
4. Omnibands heading guidance provided with 1 degree resolution/discretization
5. Omnibands altitude guidance limited within +/- 3000 feet of current ownship altitude
6. Omnibands altitude guidance provided with 100 ft altitude discretization

Well Clear Recovery Guidance

Well Clear Recovery (WCR) guidance refers to guidance that is provided to the UAS pilot to regain Well Clear from all intruders. JADEM was configured for FT4 to provide WCR guidance when no allowable ownship maneuver is predicted to *remain* well clear of all intruders. It should be noted that this implementation exceeds the minimum MOPS requirements (which only requires WCR guidance when a LoWC has already occurred). Figure 2 illustrates WCR guidance as implemented in JADEM for FT4; the red horizontal banding indicates no viable maneuvers are predicted to remain Well Clear, and the green WCR “wedge” indicates the advised direction and rough magnitude of horizontal maneuver that will result in regaining Well Clear in a safe and timely manner. Determination of a “safe and timely” maneuver is dictated by evaluation of a WCR cost function.

The JADEM WCR cost function for FT4 considers a number of factors, but is most influenced by the proximity of the predicted Closest Point of Approach (CPA) to the accepted NMAC volume and secondarily by the desire to maintain consistent WCR guidance (changes in turn direction incur a cost penalty). Finally, vertical JADEM WCR guidance was not provided for FT4 to prevent the UAS pilot from maneuvering vertically near the collision avoidance boundary against cooperative intruders (which may degrade Traffic Alert and Collision Avoidance System (TCAS) II performance) and due to vertical state estimation uncertainties for intruders tracked solely by the radar (i.e. non-cooperative intruders).

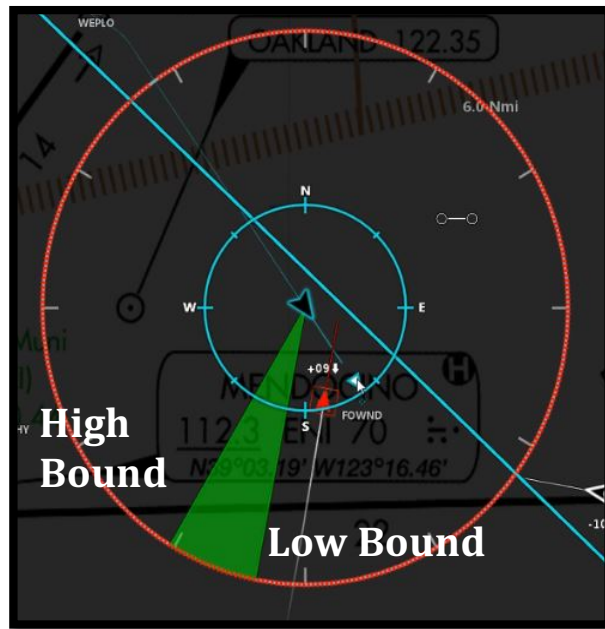


Figure 2: Sample WCR Guidance

Traffic Alert and Collision Avoidance System (TCAS) Interoperability Implementation

One of the primary objectives of FT4 was to evaluate the UAS DAA-TCAS Interoperability concept developed since FT3. The following four heuristics summarize the DAA TCAS Interoperability Concept as implemented in JADEM for FT4:

1. Any intruder with an active corrective Resolution Advisory (RA) is removed from all DAA guidance calculations
 - a. Horizontal DAA guidance will be shown for non-RA aircraft
 - b. All DAA vertical guidance is *suppressed* during a corrective RA
2. During a preventive RA, TCAS guidance is an input to the DAA vertical guidance to ensure any vertical DAA guidance is consistent (e.g. DO NOT CLIMB) with the RA guidance
3. Any time ownship's compliance with a corrective RA leads to a secondary DAA Warning alert (maneuver now), DAA guidance shall revert to well clear recovery in order to be more direct with guidance, e.g.:
 - a. Compliance with TCAS 'DESCEND' RA leads to a secondary DAA Warning
 - b. Rather than show the pilot full Omnibands suggestive guidance, limited suggestive guidance is displayed (e.g. maneuver left)

FT4 Objectives and Methodology for JADEM Analysis

Each of the FT4 systems under test (SUTs) was evaluated independently, and each according to objectives and analysis methodologies tailored to their specific implementation of the draft SC-228 UAS DAA MOPS requirements. This section describes the FT4 objectives, scenario development and analysis methodology developed and employed for the JADEM system under test.

SSI-ARC FT4 Objectives and Scenario Generation

A set of high-level test objectives were developed to support the development of the SC-228 UAS DAA MOPS. The following four high-level test objectives were used to guide the FT4 planning, conduct and analysis of JADEM alerting and guidance logic:

1. Validate DAA requirements in stressing cases that drive MOPS requirements, including: High-speed cooperative intruder, Low-speed non-cooperative intruder, high vertical closure rate encounter, and Mode C/S-only intruder (i.e. without ADS-B).
2. Validate TCAS/DAA alerting and guidance interoperability concept in the presence of realistic sensor, tracking and navigational errors and in multiple-intruder encounters against both cooperative and non-cooperative intruders.
3. Validate “Well Clear Recovery” guidance requirements in the presence of realistic sensor, tracking and navigational errors.
4. Validate DAA alerting and guidance requirements in the presence of realistic sensor, tracking and navigational errors.

In support of these objectives, a series of encounters were scripted to address each objective. The development of each scenario required identification of: the primary high-level objective being addressed, the encounter geometry, intruder equipage, data collection requirements, encounter methodology (including pilot instructions), checks to ensure data quality, draft MOPS reference, and evaluation criteria to determine whether or not the test objectives were met. A sample scenario template resulting from this process is included as Figure 3. The SSI-ARC team subsequently coordinated with AFRC flight test personnel to refine the scenarios outlined in the templates for production of flight “test cards” providing the level of detail necessary to train ownship and intruder pilots and execute the scripted scenario on the day of the flight. In total, 72 test cards were developed and flown for FT4 JADEM analysis; a sample test card is included as Figure 4.

FT4 TEST OBJECTIVES – SSIWest.2.g (FT4 encounter: 041)

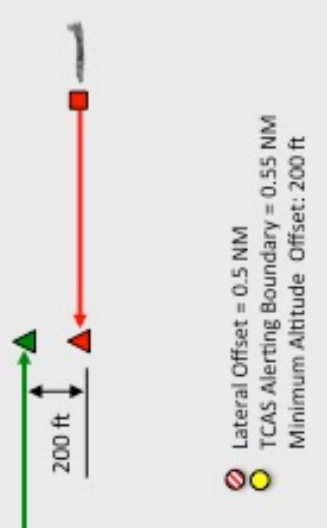
Objective 2: Validate TCAS/DAA alerting and guidance interoperability concept in the presence of realistic sensor, tracking and navigational errors: (g) level-level TCAS RA encounters (mitigated, <10kft).		MOPS Sections 2.2.4.2.4 Alerting 2.2.4.3 Determine Processing, 2.2.4.4 Collision Avoidance Interoperability									
Configuration	<p>System Under Test: Omnibands</p> <p>Display: VSCS</p> <p>Contributing Sensors:</p> <table border="1"> <thead> <tr> <th>TCAS</th><th>ADS-B</th><th>ISDB</th><th>Taxider</th></tr> </thead> <tbody> <tr> <td>YES</td><td>YES</td><td>YES</td><td>YES</td></tr> </tbody> </table>	TCAS	ADS-B	ISDB	Taxider	YES	YES	YES	YES	 <p>200 ft</p> <p>Lateral Offset = 0.5 NM</p> <p>TCAS Alerting Boundary = 0.55 NM</p> <p>Minimum Altitude Offset: 200 ft</p>	
TCAS	ADS-B	ISDB	Taxider								
YES	YES	YES	YES								
Test Objectives (TO)	<ol style="list-style-type: none"> 1. Validate DAA alert timing allows pilot sufficient time to assess options and maneuver to remain well clear. 2. Validate DAA guidance to UAS pilot is appropriate (reasonable, timely & responsive). 3. Validate DAA alerting and guidance do not interfere with UAS pilot's ability to assess and follow TCAS RA guidance. 										
Success Criteria (retest if criteria not met)	<ol style="list-style-type: none"> 1. A timely (corrective initially) DAA alert is provided to the UAS pilot. 2. A corrective TCAS RA is generated for the primary intruder and the UAS pilot complies with TCAS RA guidance. 3. Data collected: LVC log file, SAAProc log files, TCAS log files for ownship and intruder, SAAP file ("raw" surveillance data). 										
Test Method	<ul style="list-style-type: none"> • MANUEVER: Pilot disregards DAA guidance and follows TCAS guidance if consistent with test constraints. • Aircraft speeds (non-accelerating): Ownship 150 KGS, Intruder 180 KGS • Encounter Length: 1 min (IP to CPA) • Stable Conditions: stable at the IP (1 minutes prior to CPA) • Test Termination Criteria: targets diverging, range > 0.75 nmi., no DAA alerts displayed. • Climb/Roll/Pitch Rates: Ownship 0/0/0, Intruder -2500 FPM/0/0 • Tolerance: ± 8 sec, ± 5 kts at IP crossing. 										
Evaluation Criteria (Post-test analysis to determine if test objectives are met)	<ol style="list-style-type: none"> 1. UAS pilot receives DAA corrective alert with associated guidance. 2. Vertical DAA guidance indicates no viable vertical maneuvers in temporal proximity to TCAS RA. 3. DAA alerting and guidance for the primary intruder are removed while a TCAS RA is present for the primary intruder. 4. DAA alerting and guidance is generated once RA expires (if appropriate). 5. DAA alert(s) and guidance are removed once ownship is clear of threat. 		15								

Figure 3: Sample FT4 Scenario Template

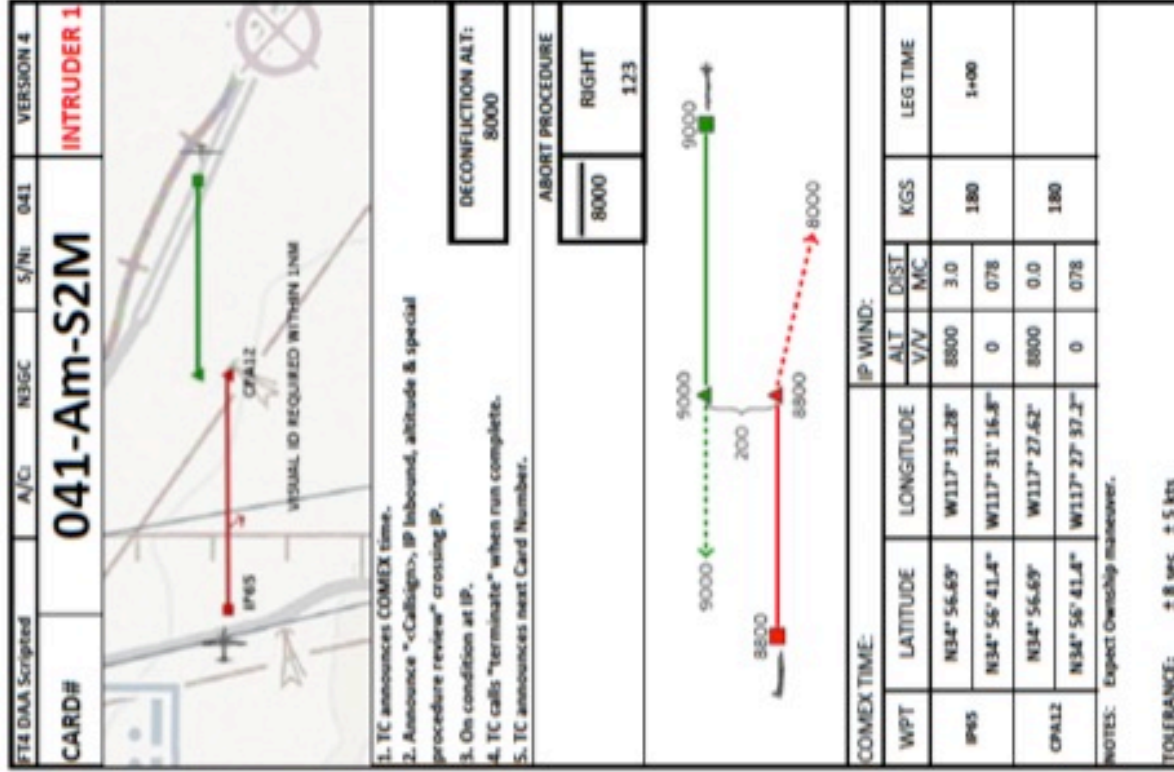
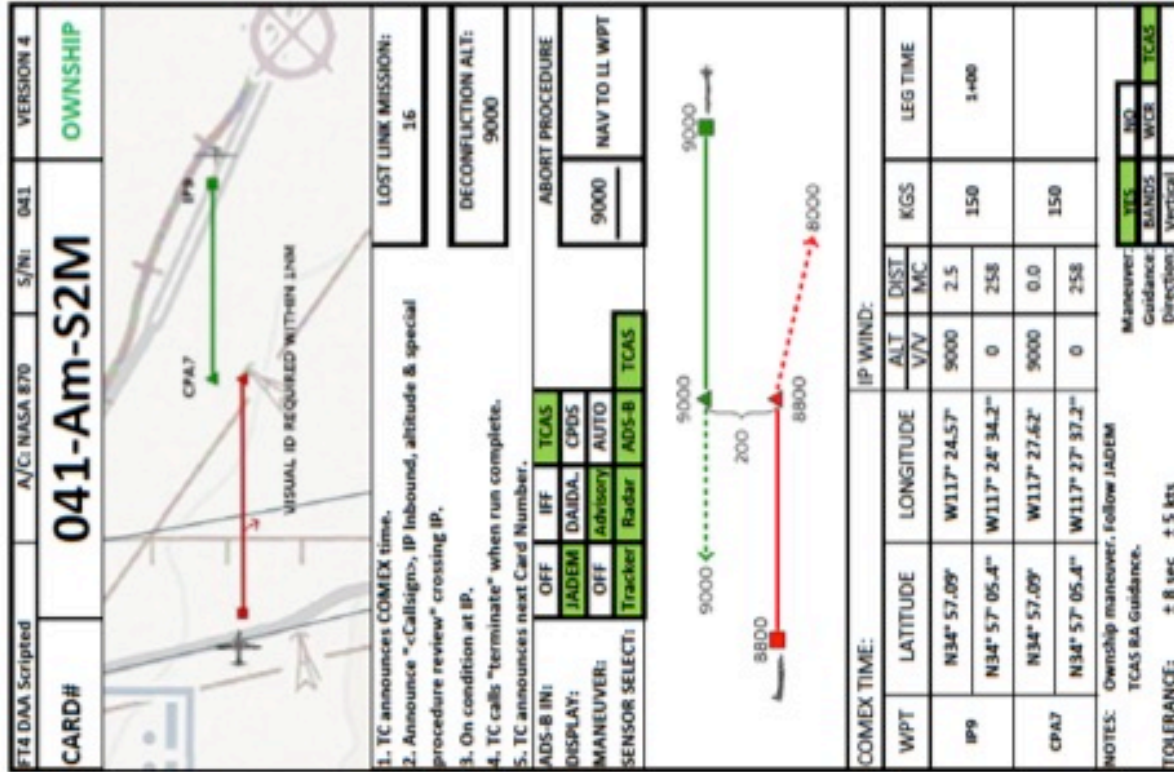


Figure 4: Sample FT4 Test Card

Analysis Methodology

The analysis methodology was designed to address the “evaluation criteria” identified for each scenario template. As such, the following key event data were extracted from the recorded flight test data for each test card:

- First Track: First recorded track for each intruder in the encounter
- DAA Preventive Alert: Onset(s) of DAA Preventive alert(s) (for each new occurrence)
- DAA Corrective Alert: Onset(s) of DAA Corrective alerts(s) (for each new occurrence)
- DAA Warning Alert: Onset(s) of DAA Warning alerts(s) (for each new occurrence)
- LoWC: Onset of each new Loss of Well Clear (may be multiple LoWCs and/or LoWC for multiple intruders)
- Regain Well Clear: first time at which Well Clear is regained after a LoWC event.
- Closest Point of Approach: time(s) at which minimum slant range is achieved during the encounter for each intruder
- TCAS Event: Time of initial TCAS Preventive or Corrective Alert and any associated guidance (or TCAS all clear message)
- Well Clear Recovery: Onset of WCR guidance and associated direction (e.g. turn right) as well as any changes to direction of guidance
- Final Alert: The last recorded alert for each intruder in the encounter
- Last Track: Last recorded track for each intruder in the encounter

These events were logged to a database that was used in the analysis to determine if events occurred in the proper sequence (e.g. TCAS Corrective RAs were preceded by DAA corrective or warning alerts) and with appropriate timing, as dictated by each encounter’s evaluation criteria. Table 2 includes the extracted events from a single FT4 JADEM encounter.

Table 2: Sample Encounter Event Table

Cycle Count	Intruder	Time	Clock Time	Event
191	N3GC	1461942437.39	15:07:17	FIRST_TRACK
198	N3GC	1461942445.37	15:07:25	DAA_PREVENTATIVE
203	N3GC	1461942450.38	15:07:30	DAA_CORRECTIVE
208	N3GC	1461942455.41	15:07:35	DAA_PREVENTATIVE
215	N3GC	1461942462.35	15:07:42	DAA_CORRECTIVE
233	N3GC	1461942480.40	15:08:00	DAA_WARNING
257	n/a	1461942504.39	15:08:24	WCR_TURN_RIGHT
258	N3GC	1461942505.38	15:08:25	LOWC
270	N3GC	1461942518.39	15:08:38	TCAS_CLIMB
291	N3GC	1461942539.39	15:08:59	CPA
291	N3GC	1461942539.39	15:08:59	TCAS_LEVEL_OFF
296	N3GC	1461942544.36	15:09:04	TCAS_AA_CLEAR
297	N3GC	1461942545.39	15:09:05	DAA_PREVENTATIVE
297	N3GC	1461942545.39	15:09:05	REGAIN_WC
300	N3GC	1461942548.40	15:09:08	FINAL_ALERT
308	N3GC	1461942556.36	15:09:16	LAST_TRACK

Also supporting the assessment of evaluation criteria were aircraft state data, alerting threat parameter data, intruder relative state data, and omnibands guidance data. Examples of data plots for each of these are shown in Figures 5-8.

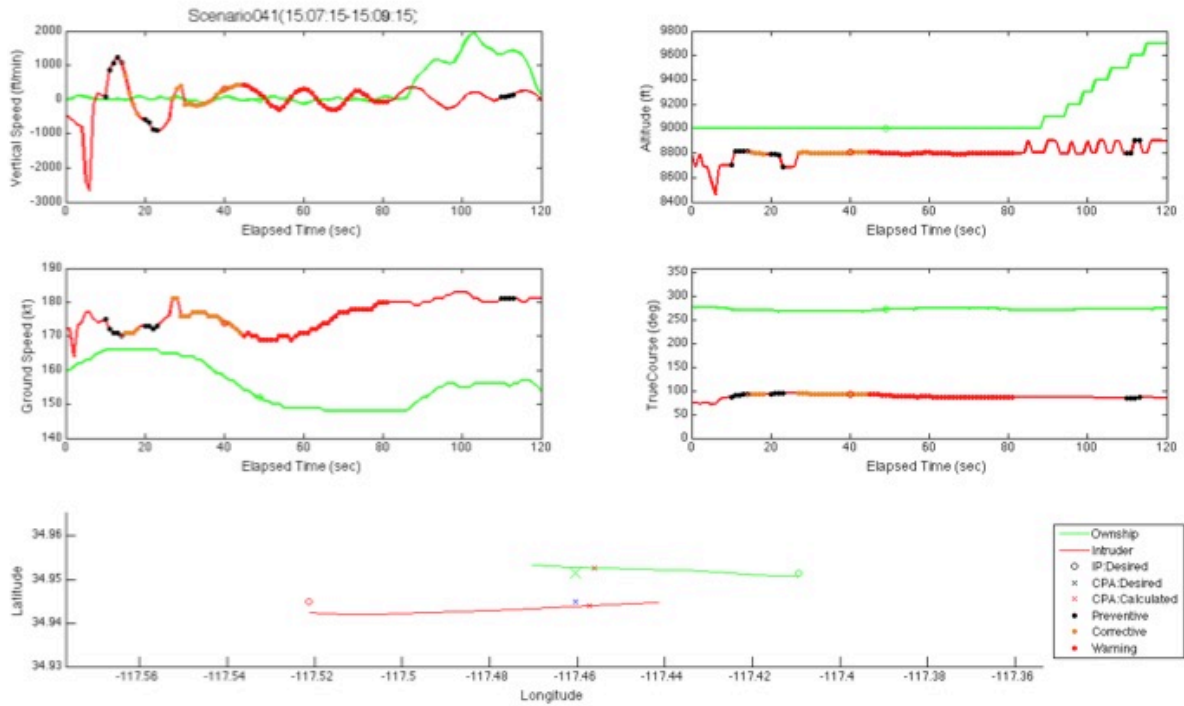


Figure 5: Sample Aircraft State Data Plots

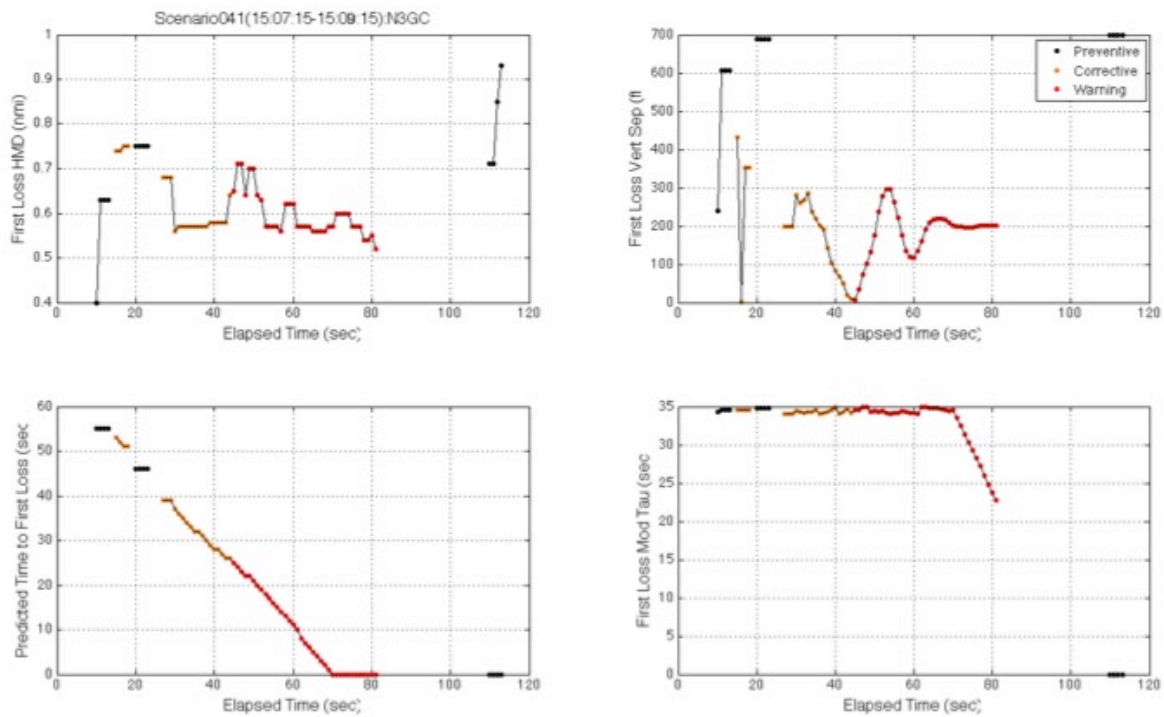


Figure 6: Sample Alerting Threat Parameter Data Plots

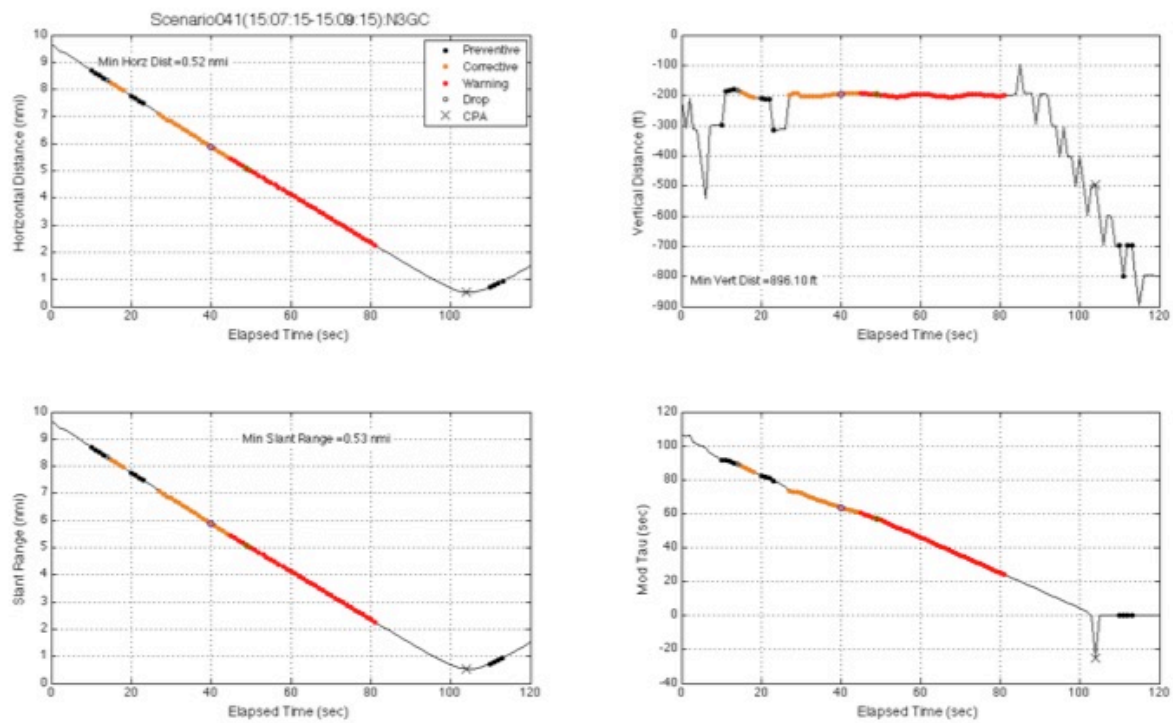


Figure 7: Sample Intruder Relative State Data Plots

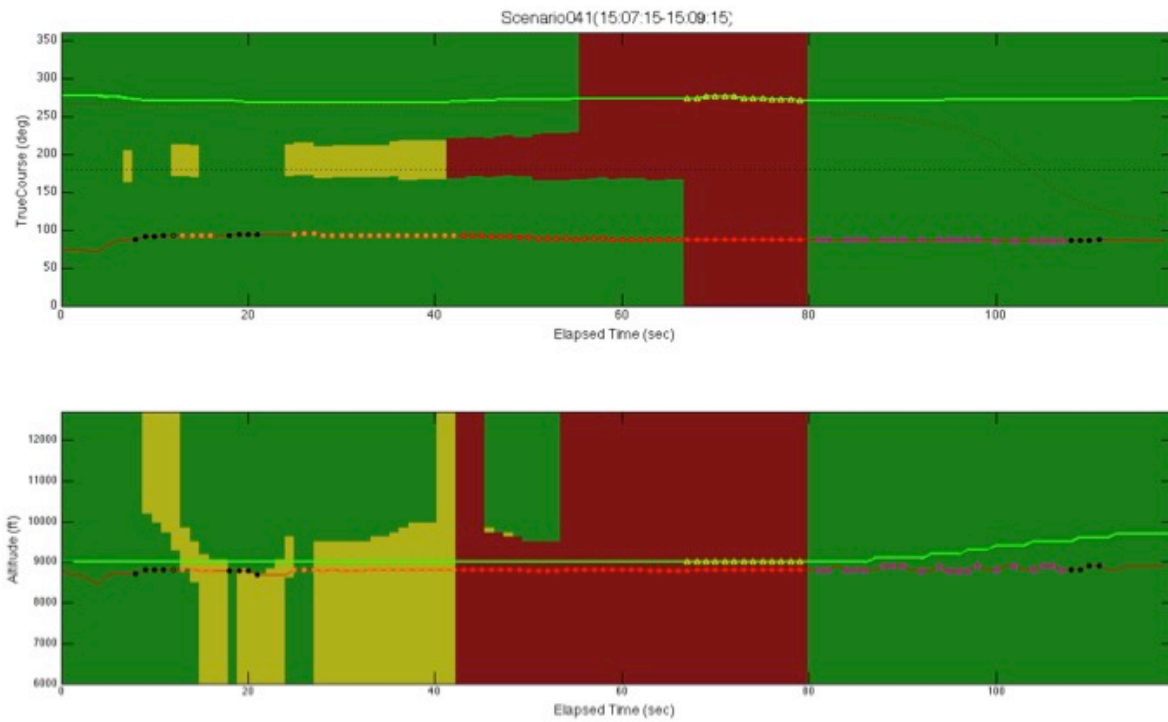


Figure 8: Sample Omnibands Data Plots

In each of the aircraft state plots (Figure 5), relative state plots (Figure 6) and alerting threat data plots (Figure 7), the color of the filled-circle markers transposed on the data plot trace indicates the type of DAA alert: DAA preventive (black), DAA corrective (orange), and DAA warning (red) alerts. Additionally, the background color coding on the Omnibands data plots (refer to Figure 8) is consistent with the Omnibands coloring predicting no LoWC (green), LoWC within 25-55 s (yellow) and LoWC within the next 25 s (red) at the indicated heading/altitude. Lastly, the Omnibands data plots also indicate when WCR guidance (yellow triangle markers) and/or TCAS RAs (magenta triangle markers) are present. Omnibands data plots were used to assess DAA-TCAS interoperability.

Finally, video recordings of the UAS DAA JADEM display were reviewed to provide any additional details necessary to assess the performance of the DAA system against the scenario evaluation criteria.

Results

Scenario Evaluation Criteria Compliance

The first element of the analysis focused on evaluation of the Boolean evaluation criteria for each scenario. Eight evaluation criteria were assessed as part of this analysis (FT4 JADEM compliance with each criterion is provided in parenthesis)

1. A DAA Corrective Alert is issued to the UAS Pilot (**94%**)
2. Ownship remains Well Clear of intruders (**90%**)
3. DAA Alerts are removed once clear of threat (**100%**)
4. DAA Alerts and Guidance are provided to the UAS Pilot following the expiration of a TCAS RA, if appropriate according to the DAA alerting thresholds (**100%**)
5. DAA Alerts and Guidance are removed for intruders with Corrective TCAS RA Guidance (**90%**)
6. Well Clear Recovery Guidance is provided when no viable maneuvers are predicted to remain well clear of all intruders (**100%**)
7. UAS Pilot maneuvers in response to WCR guidance and regains Well Clear (**100%**)
8. UAS Pilot maneuvers in response to and consistent with corrective TCAS RA guidance (**100%**)

Data analysis demonstrated a generally high level of compliance with the evaluation test criteria, with a few notable instances of non-compliance. These non-compliances were evaluated on a case-by-case basis as follows:

Failure to Provide Corrective Alert: All cases in which a DAA Corrective alert was not issued prior to higher priority alerts occurred due to the DAA Corrective and Warning Alerts having the same HMD threshold. Scenarios developed to evaluate TCAS interoperability were scripted with intruders maneuvering to intercept the course of the UAS ownship within close temporal proximity to the predicted CPA. The result of this is that the predicted modified tau of these encounters was generally below the DAA Warning Alert threshold prior to the intercept maneuver, while the predicted HMD did not meet the HMD criterion for DAA Corrective. As the intruder turned to intercept the UAS ownship, the predicted HMD rapidly decreased in value until it met the DAA Warning alert HMD threshold and a DAA Warning Alert was issued without a prior corrective alert due to the

low modified tau value at the time of the maneuver. While increasing the DAA Corrective Alert HMD value in these cases would lead to the preferred alert sequencing (DAA Corrective Alert preceding DAA Warning Alert), it is unclear if such a change is necessary. Increasing the DAA Corrective Alert HMD value should be considered in the context of the tradeoff between increased DAA Corrective Alert rate and the rate of occurrence of encounters in actual operations that would otherwise lead to the undesirable alert sequence. These non-compliances are believed to be an artifact of a carefully planned test maneuver and are expected to be uncommon in actual operations; an analysis of encounters anticipated in actual operations is necessary to corroborate this expectation.

Failure to Remain Well Clear: The evaluation criteria to remain well clear only applied to mitigated encounters in which pilots were instructed to follow DAA guidance. For such encounters, UAS pilots were instructed to: 1) postpone maneuvers until a DAA Warning Alert had been issued, 2) maneuver to the edge of the green guidance band in the direction of their choice (if more than one option was provided), and 3) to only maneuver once (no corrections to initial maneuver allowed). These instructions were provided with the intention of isolating JADEM performance from the pilot's ability to accommodate shortcomings in DAA system performance in remaining Well Clear (e.g. by adding his/her own excess maneuver buffers or making adjustments to the initial maneuver to counter poor JADEM trajectory predictions or guidance instabilities). Such pilot response to a DAA Corrective Alert in operational use of JADEM would be consistent with a pilot assessing the predicted LoWC, and delaying maneuvering pending further development of the encounter or until a higher priority task is completed. While delaying UAS maneuvering to avoid LoWC until a DAA Warning Alert is received should generally not lead to LoWC, such delays would result in higher rate of LoWC (acceptable rates of LoWC in this case are beyond the scope of FT4). The pilot instruction to only maneuver once for a given encounter removes the pilot's ability to react to the uncertainties of developing encounters and artificially increases the rate of LoWC; refinements to UAS maneuvers to remain Well Clear are to be expected in actual use of a DAA system. Given the pilot instructions in the use of JADEM in FT4, it is somewhat surprising that LoWCs only occurred in 2 of the 20 mitigated encounters. Both instances were the result of modest intruder accelerations: increased ground speed in one case and a slowly arcing turn toward the UAS in the second. It is likely that both LoWCs would have been avoided with earlier ownship maneuvering (in response to the initial DAA Corrective alerts) and the allowance of maneuver adjustments to account for maneuvering intruders.

Failure to Remove DAA Guidance for Intruders with Corrective RA Guidance: The TCAS interoperability concept implemented for FT4 required that intruders involved in a TCAS corrective RA be removed from consideration for DAA Alerting and Guidance consideration. While this was implemented in the JADEM software, 3 instances of concurrent JADEM DAA and TCAS RA guidance were observed during FT4. Each of these instances were determined to be the result of a software issue unrelated to the interoperability concept and is considered a test artifact not indicative of system performance.

DAA Alert Timing

DAA alert timing was analyzed to assess the efficacy of JADEM DAA alerts in a realistic environment, including stressing encounter geometries and surveillance sensor error. The DAA alert timing analysis was limited to unmitigated encounters to remove the influence of pilot actions on the results and because some of the metrics are referenced to initial Loss of Well Clear.

DAA Alert Lead Time: Figures 9 and 10 provide histograms of DAA Corrective Alert lead time and DAA Warning Alert lead time, respectively. Lead time is defined as the elapsed time between the initial alert of a given priority (e.g. first DAA Warning alert issued to the UAS pilot during an encounter) and the initial LoWC. The observed mean DAA Corrective alert lead time was 46 s and the mean DAA Warning alert lead time was 23 s. The lead time for DAA Corrective alerts in the absence of a DAA Corrective alert was assigned the same lead time as the DAA Warning alert; that is, the first time at which all the alerting thresholds for the DAA Corrective alert are met. When these encounters are excluded from the analysis, the mean DAA Corrective alert lead time is higher: 49 s.

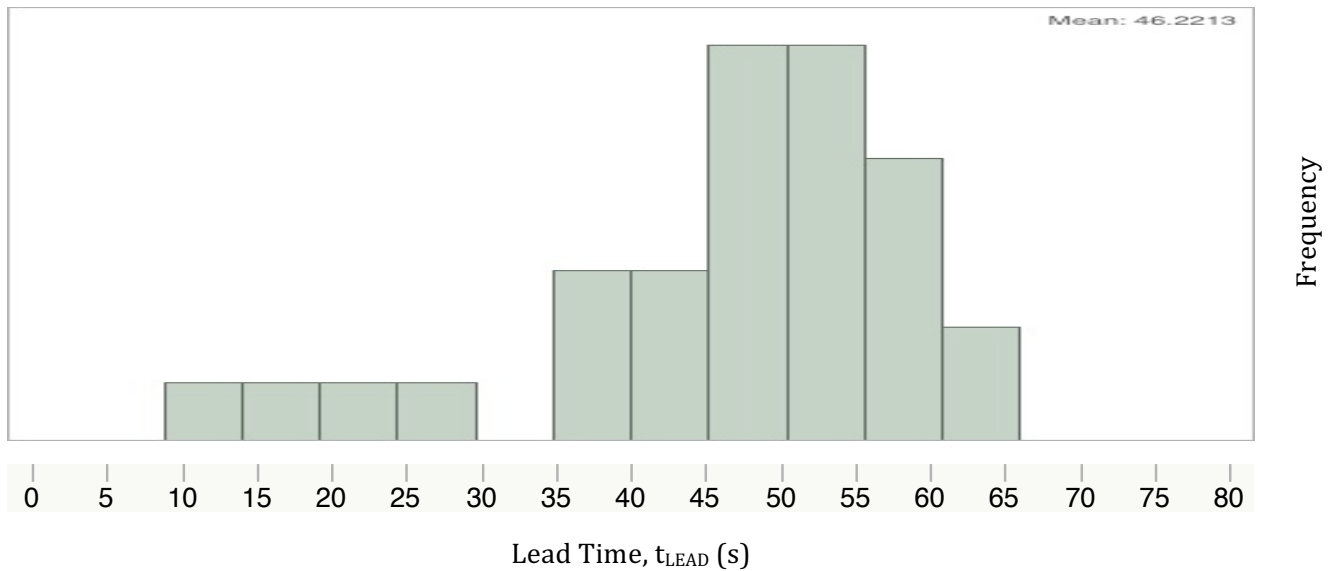


Figure 9: DAA Corrective Alert Lead Time Histogram

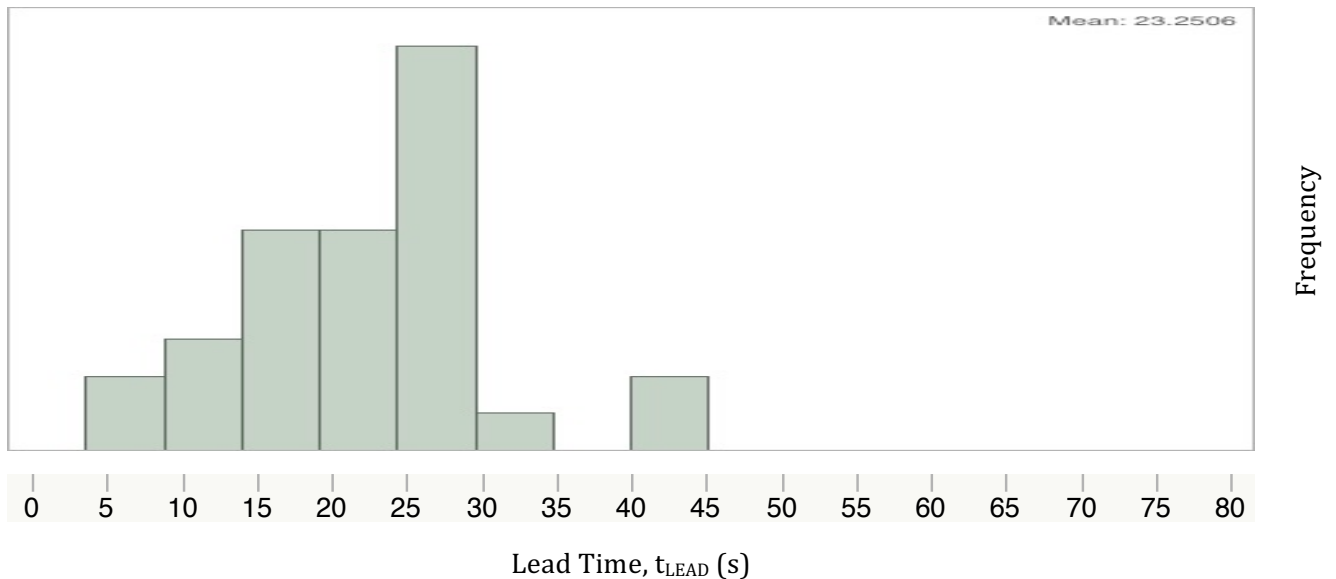


Figure 10: DAA Warning Alert Lead Time Histogram

DAA Alert Transition Time: Alert transition time is defined as the elapsed time between a given alert priority level and the next highest alert priority level (e.g. transition time between initial DAA Corrective alert and initial DAA Warning alert). Table 3 provides the mean transition times between alert priority levels; the results are consistent with expectations given the modified tau values for each alert level, as specified in Table 1. No firm conclusions can be drawn from the mean transition times in Table 3 due to the limited sample size and operational coverage of the FT4 encounter set.

Table 3: DAA Alert Transition Time

Alert Transition	Mean Transition Time (s)
DAA Preventive to DAA Corrective	3.2 s
DAA Corrective to DAA Warning	24.9 s
DAA Warning to Well Clear Recovery	19.3 s
Well Clear Recovery to TCAS	9.7 s

DAA TCAS Interoperability

As discussed in the preceding evaluation criteria compliance section, compliance with the required elements of the DAA-TCAS interoperability concepts was largely met, with few exceptions being the result of JADEM software implementation issues. Of note, two scenarios resulted in corrective TCAS RAs while JADEM deemed the ownship Well Clear of the intruder with green banding guidance at the time of the corrective TCAS RA. Further analysis by SC-228 personnel and TCAS-II experts concluded that such “Well Clear RAs” observed in FT4 are the result of incompatibility between DAA Corrective Alert HMD threshold (0.75nm) and how HMD is used (or in this case, NOT used) to filter TCAS RAs. In these two cases, it was concluded that TCAS did not consider HMD in issuing a corrective RA due to the close proximity of the intruder and the expected error in the HMD prediction. Based on this finding and consistent observations with all systems under test in FT4, it is recommended that the MOPS Alerting requirements be refined to consider TCAS employment of the HMD filter and to mitigate its impact on alerting performance.

Mode C Intruder Guidance Stability

Analysis of JADEM guidance stability for intruders lacking ADS-B equipment was considered a secondary priority of the data analysis. When Mode C surveillance is the only available bearing source for the DAA system, a high degree of bearing uncertainty is to be expected. Unfortunately, only three FT4 JADEM encounters included intruders with transponders but without ADS-B equipage. Further, the JADEM guidance for these encounters was based on a fusion track that included radar surveillance (i.e., has low bearing error within the radar detection range). Thus, while the observed guidance demonstrated excellent stability for these three encounters, more analysis is needed to draw any conclusions about the stability of JADEM DAA guidance for Mode C Intruders. However, it is unclear if this should be considered a priority for further investigation given the expectation that intruders will generally be within radar range prior to the prescribed alerting thresholds (i.e. bearing error is not expected to influence DAA alerting).

WCR Performance

While WCR performance met the objective criteria prescribed in the scenario evaluation criteria, FT4 UAS pilot participants subjectively assessed WCR performance as lacking in a number of areas. First, WCR guidance stability was deemed poor for intruders lacking ADS-B equipage; such encounters demonstrated multiple changes in the WCR guidance direction that pilots found distracting or lacking informative value. Second, UAS pilots objected to WCR guidance that prescribed turns to headings aft of the current UAS course; such turns would require significant deviation from planned route of flight, would result in significant time in close proximity for head-on encounter geometries, and often place non-cooperative intruders outside the surveillance volume.

Concluding Remarks and Recommendations

FT4 provided a unique opportunity to evaluate the performance of a prototype UAS DAA system (NASA JADEM) across a range of encounter conditions and in a realistic flight environment including surveillance system errors. However, as with all flight tests, FT4 was a tightly controlled experiment with prior pilot knowledge of encounter geometry and intruder “escape” procedures. As such, while the performance of the UAS DAA system employed in FT4 is evaluated for the purpose of furthering MOPS development, the results must be considered in the context of FT4 and in combination with results from other UAS DAA experiments (e.g. NASA PT5 and NASA PT6, where the UAS pilots had no advance knowledge of encounters and intruder actions). However, whereas human-in-the-loop simulations use models of aircraft dynamics, surveillance sensors and atmospheric phenomena, flight test offers a glimpse at the performance of the prototype UAS DAA system under real-world conditions; it is through this lens that the performance of the prototype UAS DAA system is assessed. DAA system performance was assessed across five categories of metrics: Alert Timing, UAS DAA-TCAS Interoperability, Mode C Intruder Alert Stability, Well Clear Recover Performance and a broad set of Scenario Evaluation Criteria.

Observed alert lead times indicated acceptable UAS DAA alerting performance; mean DAA Corrective and DAA Warning alert lead times were 46 and 23 seconds respectively. Excluding encounters that included turns toward the intruder (with the explicit purpose of creating immediate TCAS RAs), the DAA Corrective Alert lead time increased to 49 s. These mean lead times are consistent with (albeit slightly below) the MOPS average alert lead times (Section 2.2.4.3.4.), and are indicative of acceptable alerting thresholds implemented within JADEM for FT4.

FT4 included 29 JADEM scenarios to investigate the UAS DAA-TCAS interoperability concept. Results indicate effective interoperability across the range of test conditions with one notable exception case: the “Well Clear RA”. Observed for a small number of scenarios (and across all systems under test), UAS pilots were presented with a TCAS RA while the UAS DAA system had determined the intruder to be Well Clear. It was determined that such RAs were due to suppression of the Horizontal Miss Distance (HMD) criterion test when TCAS deemed the intruder bearing information to be of insufficient quality. Because TCAS does not have a quality bearing surveillance source (e.g. ADS-B or airborne radar), such cases are to be expected, and it is recommended further analysis be conducted to determine the rate of occurrence of such RAs in the NAS and potential mitigations, if needed.

Observations on the stability of alerts for “Mode C-only Intruders” were limited to a single scenario in FT4. As such, more data is necessary to draw firm conclusions on the acceptability of UAS DAA

system performance for such intruders. The concern regarding alert instability for Mode-C-only intruders stems from the poor bearing information derived from transponder replies alone. However, given the airborne radar equipage requirement and typical radar detection range, it is unclear if such intruders represent a credible concern regarding alerting stability; bearing error should be a non-issue once the intruder is within radar detection range. Further analysis of Mode C intruder alert stability should thus consider radar detection range and the bearing performance of an integrated intruder track.

Nine scenarios were conducted to assess the performance of UAS DAA Well Clear Recovery (WCR) guidance to the UAS pilot. While observations indicated effective WCR guidance for ADS-B equipped intruders, guidance was deemed largely ineffective for other intruders for a number of reasons. First, UAS pilots indicated (and data confirmed) some directional instability in WCR guidance; it is recommended that additional heuristics and/or hysteresis be included in WCR logic to prevent frequent changes in the directional WCR guidance. Second, WCR guidance occasionally included turns well beyond 90 degrees from the current course; UAS pilots found this objectionable and ineffective. It is recommended that WCR directional guidance be limited to turns of less than some reasonable bound (e.g. 90 degrees from current course).

Finally, a broad set of scenario evaluation criteria were collected to assess high-level UAS DAA system performance. Compliance with scenario evaluation criteria is considered indicative of acceptable UAS DAA performance. FT4 JADEM scenario evaluation criteria compliance exceeded 90% and non-compliances were assessed to be either test artifacts or the results of a (since corrected) software coding error. While no acceptance threshold for evaluation criteria compliance was established, the observed high level of compliance provides anecdotal evidence for requirements validation of the alerting parameters, WCR guidance logic and TCAS interoperability concept implemented within JADEM for FT4. Finally, it is important to reiterate that the results presented herein are based on a limited set of scripted scenarios executed in a tightly controlled flight test environment with well-rehearsed and limiting pilot procedures for use of the system under test; the results, conclusions and recommendations included in this document provide key insights and anecdotal evidence, but represent a small fraction of the analyses necessary to fully validate the SC-228 UAS DAA MOPS requirements.